Issues in Vehicle Teleoperation for Tunnel and Sewer Reconnaissance

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Abstract

With the introduction of the Man Portable Robotic System (MPRS), things are about to change for the next generation of military engineers (tunnel rats) tasked with tunnel and sewer reconnaissance. No longer will there be a need for soldiers to descend below the surface into a hostile environment, blindly crawling through rubble and mud while probing ahead for explosives with a bayonet. This paper presents a comprehensive overview of the MPRS and its associated Operator Control Unit teleoperation interface, with an emphasis on lessons learned during preliminary and interim testing.

1 Background

Tunnels and sewers provide a good alternative means of travel and communication when a superior military force controls the air and ground above. The dangerous and labor-intensive process of searching and clearing underground labyrinths has seen little change over the last century. The early tunnel rats soon discovered that the standard infantryman's equipment was ill suited for the task at hand, and in fact, the less gear a soldier took underground, the better his chances of survival. Indeed, the very reverse of high-tech weapons development took place within the elite corps of the tunnel rats: a bayonet, pistol, and flashlight were the basic tools of choice.

Booby traps are just one of the dangers associated with underground operations. Very likely there may be hostile forces laying in ambush, and an advancing soldier with a flashlight makes an easy target. But the situation is changing for the better with the advent of the Man Portable Robotic System (MPRS). These teleoperated robots will be used to detect hostile entities, locate/deactivate booby traps, deliver payloads, or simply stop, look, and listen, keeping the soldier safely removed from the hazards involved.

Such tactical mobile robots require a simple and easy to use interface to effectively support military applications in highly unstructured urban settings. On the low end of the spectrum, a purely teleoperated system can facilitate remote operation in hostile underground environments, provided the mission time is not too extensive. At the high end, a computer-assisted telereflexive system can ease the driving burden by modifying the operator's desired motion commands based on perceived obstacles, thereby reducing fatigue [1]. There are significant pros and cons associated with either approach.

2 MPRS Design Philosophy

The MPRS program goal is to develop lightweight (i.e., man-portable) mobile robots for operation in urban environments (indoor, outdoor, and underground). The technical strategy calls for optimizing a realistic and robust solution to an appropriate set of articulated user requirements, using predominantly off-the-shelf components. The capabilities and sophistication of these systems will expand with time as new technologies become available from various sources.

Effective navigation and control of urban scout-type robots inside tunnels and other structures currently present several challenges. Basic teleoperated-control concepts support only limited remote operation; overall effectiveness is rather low, and degrades rapidly due to operator fatigue. The additional burden of keeping track of the robot's position and orientation using the limited information gathered from an onboard video camera taxes even a highly skilled operator. This situation is further complicated by potential video signal degradation, poor lighting, and little or no scene contrast.

Experience gained through actual use by law enforcement and military personnel of conventional teleoperated devices with minimal onboard intelligence has revealed other shortcomings from a man/machine interface point of view if multiple input devices are

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required for motion, camera pan and tilt, and perhaps even a weapon system. For these reasons, the initial MPRS system was implemented under a reflexive teleoperated control interface supported by ultrasonic and near-infrared collision avoidance sensors, as discussed in the next section.

3 First-Generation MPRS Prototype

Traditionally, the fundamental problem faced by robotic systems integrators has been to match the requirements of the users, who typically don't understand the strengths and weaknesses of the technology, to the solutions proposed by technologists, who routinely do not understand the user's application. To bridge this gap, a preliminary prototype was developed to facilitate meaningful user feedback that influenced the follow-on design of a more capable second-generation solution.

This section describes the first-generation MPRS prototype that was evaluated in conjunction with the US Army Combat Engineers Tunnel and Sewer Concept Experimentation Program (CEP) held at Ft. Leonard Wood in the fall of 1999 [2]. The purpose of the CEP was to validate the concept of employing small robots to conduct tunnel, sewer, and bunker reconnaissance in urban combat. The soldiers operating the robots during these exercises were from the 41st Engineer Battalion, 10th Mountain Division, Fort Drum, NY, and the 577th Engineer Battalion, Fort Leonard Wood, MO.

3.1 Robotic Vehicle

The first-generation prototype was based on a modified Foster-Miller *Lemming* base. The stock *Lemming* is a small, inexpensive (basically expendable) tracked robot that can be remotely operated with a simple joystick or push-button controller via an RS-232 serial RF link, equipped with an on-board video camera and associated analog transmitter. The MPRS configuration (Figure 1) employed the mechanical elements (chassis, drive motors, gearboxes, tracks, and drive sprockets) of the *Lemming*, but substituted more sophisticated electronics, sensors, and an upgraded Operator Control Unit (OCU).

Figure 1. Front view of the first-generation MPRS prototype and associated OCU.

The collision avoidance sensors are located in a watertight "Sensor Snout" at the front of the vehicle (Figure 2): three forward- and two side-looking sonars, and two five-element arrays of Sharp near-infrared triangulation ranging sensors. Also inside the Snout are two miniature pin-hole cameras with dual halogen headlights. The platform was designed to be fully invertable (i.e., can operate upside down or rightside up with no preference), as opposed to self-righting. An attitude sensor automatically determines which set of Sharp rangefinders and which video camera to use in case the robot flips over. The onboard software also inverts the sense of incoming drive and steering commands to preserve a normal mobility response. A pair of Precision Navigation electronic compasses located within the Snout provide magnetic heading, pitch, roll, and ambient temperature (two compasses are required to support inverted operation).

Figure 2. Front-mounted Sensor Snout showing the dual headlights, Sharp I/R arrays, and three forward sonars.

Two processors are used to control vehicle functions. The primary processor, located in an electronics box behind the Snout, is responsible for driving (navigation) and telemetry functions. A secondary processor within the Snout is responsible for sensor data collection and headlight intensity (PWM) control. Both processors are 66-MHz PowerPC-based *ipEngines* from Brightstar Engineering.

The electronics enclosure also houses a differential GPS receiver that can be used for vehicle navigation when operating above ground. A text-to-speech voice synthesizer is employed to inject audio prompts into the telemetry stream returning to the controller, and to output warning messages at the vehicle. A six-channel audio mixer is used to route audio signals between the robot and the controller. Real-time digital video and audio (along with command and control data) are passed between the robot and the OCU over a wireless Ethernet link. The digital video/audio system (from Indigo Active Vision Systems) employs a hardware-based CODEC that provides between 15 and 20 frames of digitized video per second. The CODEC is also capable of providing bi-directional audio between the OCU and the robot, which allows for two-way verbal communication with a hostile element.

3.2 Operator Control Unit

The MPRS OCU (Figure 3) is a portable self-contained teleoperation interface packaged as three subassemblies: the electronics box, battery box, and control pendent. The electronics box contains the OCU processor, another *ipEngine* running a real-time POSIX-based operating system. Also in the electronics enclosure is a video decoder for the digital video, a video overlay board to superimpose status information and menu selections on the video display, a small Ethernet hub, and a 2.4-GHz modem. The battery box contains four 7.2-volt NiMH battery packs and a five-volt switching regulator.

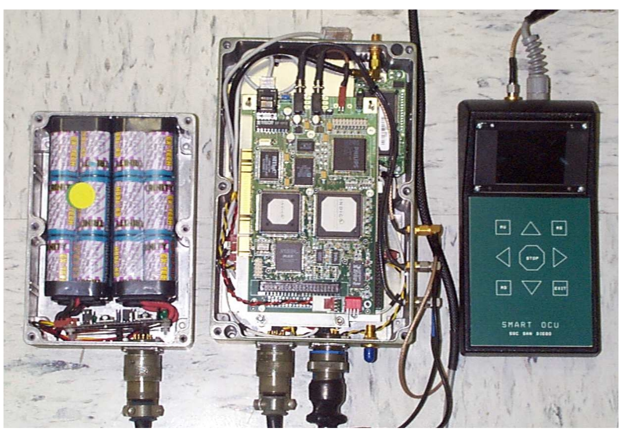

Figure 3. OCU components from left to right: battery pack; electronics (includes Ethernet modem, *ipEngine* processor, video overlay board, and video digital decoder); and hand-held video/control pendent.

The control pendent employs an array of capacitive touch-sensor icons for user input, based on the Quantum Research *QProx E6S2* matrix decoder, to facilitate operation by a user wearing heavy gloves associated with protective Chem-Gear. A high-resolution 2.5-inch color Thin-Film-Transistor LCD monitor provides video output for the selected camera, in addition to vehicle status information (Mode, Heading, Speed, Pitch, Roll) overlaid at the top of the screen.

A user-friendly reflexive teleoperation interface, originally developed for ROBART III [3] (see also companion paper these proceedings), was simplified and then ported over to the MPRS system. Touching the forward arrow on the pendent (Figure 4) increases the speed of the robot by one increment, whereas touching the left or right arrows imposes a differential bias on the forward speed, causing the platform to turn. If the forward (or reverse) speed is zero (i.e., platform stopped), touching a turn arrow causes the robot to pivot in place. The commanded drive speed and direction are maintained until altered by the user or otherwise modified by the onboard collision-avoidance algorithms in response to sensor inputs.

Figure 4. The initial MPRS control pendent employed an integrated 2.5-inch video display and capacitive touch pad for semi-hands-free operation.

4 User Feedback

Preliminary user evaluations of the first MPRS prototype and a family of assorted OCUs in tunnel exploration exercises at Ft Leonard Wood, MO have shown, however, that sophisticated telereflexive operation, even with a simple user interface, was neither required nor desired by the operators. Some of the specific lessons learned during the CEP that directly influenced the MPRS redesign are discussed below.

4.1 User Interface

Reflexive teleoperated control in essence provided more sophistication than the soldier required at this initial stage of MPRS evolution. During a search mission, the robot needs to move slowly and stop often, allowing the operator sufficient time to closely examine the video for anything of tactical significance. Accordingly, a purely teleoperated strategy was specifically requested, giving the user direct control over every aspect of the system. This approach presumably allowed more in-depth searching of the underground tunnel network. While reflexive teleoperation may facilitate quick exploration and mapping, the primary job of the robotic "tunnel rat" is to assess structural integrity and detect obstacles and other hazards, not blunder into them. Effective execution of these tasks, in the early stages at least, will require slow and meticulous movement and analysis of high-resolution video.

Sweeping turns (differential turns while moving forward or reverse) was another feature the soldiers did not desire. In a narrow tunnel there are basically only four choices: forward, backward, turn 90-degrees right, or turn 90-degrees left. The users therefore requested a simple pivot-in-place turning capability to further simplify the man-machine interface.

In general, controlling the robot was much harder for the soldiers than expected. The capacitive touch pad was too susceptible to erroneous input (i.e., it was easy to accidentally touch the wrong key). As a result, the user was forced to constantly look at the control pendent to verify the correct finger position on the pad, which became a real challenge in the dark. Even under ideal conditions, this unacceptable distraction significantly interfered with the need to closely assess video. The general consensus was that a small hand-held input device with appropriate tactile feel was required to support one-hand operation in total darkness.

A number of video display configurations were evaluated in conjunction with the CEP. One option involved a heads-up-display (HUD) worn on the head and viewed with the left eye. The video quality was fairly good when the operator was inside the tunnel, but users typically had to shield the eyepiece with both hands when outdoors to block out the glare of the sun.

Another drawback associated with the HUD was that only one person could view video at a time. (An emergent requirement from these exercises was the ability to have a second viewer to assist in video analysis.) In addition, the helmet configuration of the HUD proved to be incompatible with the protective "Chem Gear" the users often wore. An alternative video solution incorporating a 2.5-inch LCD color monitor into the hand-held control pendent (see again Figure 4) proved bright enough even in direct sunlight, but a second soldier had a hard time seeing the video due to the small screen size.

4.2 On-board Camera(s)

The ultimate success or failure of a robotic "tunnel rat" in its currently envisioned role will depend for the most part on the operator's ability to reliably assess video. Valuable user feedback was obtained during the CEP with respect to a number of issues in this regard. For instance, viewing video with the robotic platform in motion was generally difficult for several reasons: 1) significant breakup and signal degradation of analog transmissions; 2) slow update rate and hence lag of some of the digital versions; and 3) frame-to-frame jitter due to mechanical vibration. The bottom line was that the near-real-time digital transmission and electronically stabilized video incorporated on the first-generation MPRS prototype offered partial or complete solutions to several noted concerns.

The fixed-focus color pinhole cameras located in the Sensor Snout provided a great view of anything located directly in front of the robot, but unfortunately this perspective tended to be too close to the ground. Since all objects of interest may not be in the plane of the robot, the soldiers quickly identified a need to tilt the camera both up and down. For example, as the robot climbs upward when breaching an obstruction, the forward-looking camera is actually pointed directly at the ceiling, instead of observing the obstacle being surmounted.

Another problem with the original Sensor Snout camera field-of-view was that the soldiers could not see the left and right drive tracks to get a feel for actual robot orientation with respect to the obstacles ahead. From these observations emerged a requirement for a removed-perspective driving camera looking forward, but mounted towards the very back of the platform. It also quickly became apparent that after entering a narrow tunnel system, the robot may not be able to turn around when it came time to exit. This scenario forced the operator to drive backwards, and highlighted the need for a dedicated rear-facing camera equipped with an integral near-infrared illuminator.

A final complaint was the lack of a zoom feature on the pinhole camera. This missing functionality precluded the operator from getting a good look at anything of interest without physically moving the robot very close to the object, which was not always feasible. It was also apparent to some of the SPAWAR engineers supporting the CEP that the ability to manually zoom and focus the surveillance camera would be very advantageous in optically isolating (and hence detecting) a camouflaged trip wire suspended across the vehicle path.

5 Second-Generation MPRS Prototype

Based on the extensive user feedback obtained from on-site evaluations at the Fort Leonard Wood CEP in late fall of 1999, a number of significant changes have been incorporated into the design of a much-improved second-generation MPRS platform, as discussed in the following subsections.

5.1 Platform Upgrades

The platform chassis was upgraded from the *Lemming* to a variant of the six-wheel Foster-Miller *Tactical Adjustable Robot (TAR),* with the length fixed at 33 inches (i.e., no longer adjustable) to save weight. The center sprocket was increased in diameter from 10 to 11 inches, thus providing 0.5 inches of "high-center" effect (even if inverted) to facilitate turning. In addition, the onboard battery capacity was effectively doubled for extended mission endurance, and equipped with an integral recharging circuit to minimize required support equipment.

A Sony EVI-330/T camera system was installed in an articulated Sensor Snout with the capability to tilt as much as 90 degrees above or below the horizontal. Equipped with a 12X mechanical zoom, 24X digital zoom, auto-iris, and automatic focus, the Sony system also has provision for external computer control (via an RS-232 interface) of these same parameters. This enhanced surveillance camera is ideal for viewing detail, and built-in electronic image stabilization effectively smooths out mechanically induced jitter, especially when operating over sections of corrugated pipe. But the up-front-down-low perspective from the Sensor Snout is not at all well suited for remote driving.

Accordingly, a low-silhouette pair of fixed-focus auxiliary "drive cameras" were added to the top and bottom cover panels for the robotic chassis. This mounting configuration provides an approximated over-the-shoulder viewing perspective that includes the left and right forward drive sprockets, thereby significantly augmenting the operator's perception of vehicle orientation with respect to perceived obstacles. An additional fixed camera was mounted on the rear of the robot to support driving in reverse.

5.2 OCU Upgrades

The capacitive touch pad employed on the first-generation control pendent has been replaced by a pushbutton array that provides excellent tactile feedback for unambiguous one-hand operation in total darkness (Figure 5). Direction of travel is controlled by pressing and holding the appropriate button (i.e., forward, reverse, left, or right). The platform stops immediately as soon as the button is released.

Figure 5. A star pattern of pushbuttons provides directional control (i.e., left, right, forward, reverse), while speed is set using the potentiometer (right center of photo) on the end of the pendent housing.

Speed is controlled by a potentiometer that can be easily adjusted with the index finger (Figure 5), or alternatively using a pair of up/down buttons on the side of the case (Figure 6). A decision as to which speed-control option is incorporated in the final design will be made after some additional user tests to evaluate functional utility while the operator is fully outfitted in protective MOPP IV Chem-Gear.

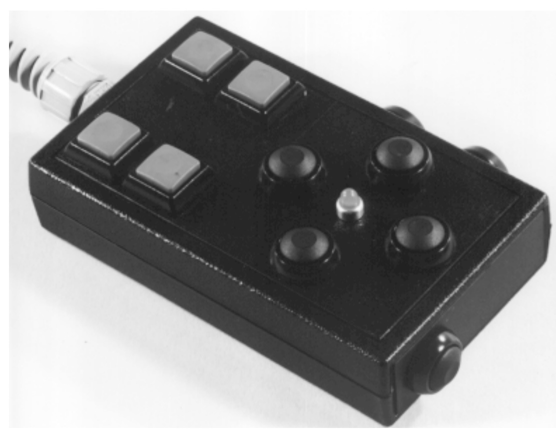

Figure 6. An alternative pendent configuration employs a pair of up/down buttons on the left side of the enclosure (upper right in photo) for velocity control.

Menu selection is now loop-scrolled with a pushbutton located on the top end of the pendent (lower right corner of Figure 6). Pressing the button once momentarily activates the menu overlay at the top of the video screen. Pressing the button again while the overlay is active advances the highlight cursor one increment at a time through the various menus (i.e., zoom, focus, headlight intensity, camera select). Options within the highlighted menu are then accessed/modified with a pair of up/down buttons on the lower right side of the pendent face. A dedicated up/down button pair is provided for tilting the Sensor Snout in anticipation of its frequent use. Note the first pendent configuration (Figure 5) employs rocker switches in place of the button pairs.

A detached 5-inch active matrix LCD panel (Figure 7) has been selected to keep the pendent size small enough for one-hand operation, and to make the video more accessible to an observer looking over the shoulder of the primary operator. The waterproof enclosure is attached using a Velcro fastener to the user's forearm (left or right), which facilitates the short-term solution for inverting the video in the event the robot flips over. (The digital video will eventually be automatically inverted in software, but not in time for the initial delivery of four systems in the spring of FY-00.)

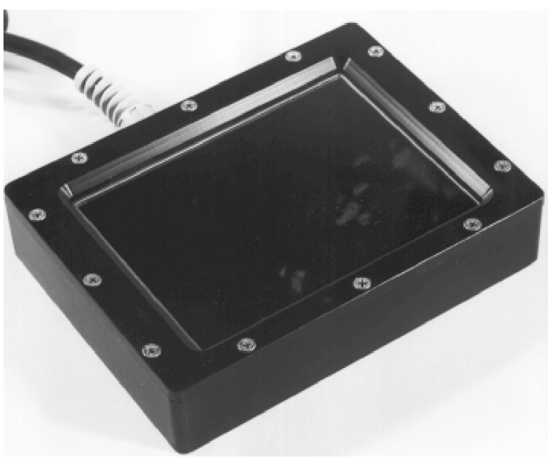

Figure 7. A larger 5-inch video display enclosed in a separate watertight housing allows for easier viewing by a second soldier (i.e., observer).

6 Conclusion

In the past, the "tunnel rat" was to realize that not even superior firepower, advanced technology, or personal armor would ever give him a decided advantage over the invisible deadly threats often hidden in tunnels. A barefoot, malnourished enemy soldier armed with only a small caliber pistol, for example, could easily represent a fatal encounter, given the element of surprise. Years later, MPRS has made the job of underground tactical search and surveillance easier and safer by relocating the operator to a removed vantage point far away from immediate danger.

Surprisingly, from a technical perspective anyway, early military users of the first MPRS prototype backed away from any computer-aided telereflexive driving assistance in favor of direct teleoperation. In retrospect, there were probably three major reasons for this preference. For starters, a general unfamiliarity with robotic systems on the part of military personnel used to "moving carefully" in a hazardous environment was probably a factor.

Secondly, the decidedly nonplanar operating environment, wherein the third (vertical) dimension plays a much bigger role, had a significant impact on algorithm performance, relative to previous applications [3]. In a typical building interior, the floors are generally level surfaces, and objects can be simplistically represented in terms of their projection on the X-Y plane. It is then a fairly simple matter to turn left to avoid objects on the right, and so forth. The situation is somewhat convoluted if the orientation of the platform changes significantly with respect to the horizontal plane, as when climbing over obstructions, and the success of any automated avoidance maneuvers degrades accordingly.

Probably the biggest factor of all was simply the very nature of the mission, which dictated slow and methodical forward progress contingent upon good video assessment along the way. The user was most comfortable in this environment with a control philosophy that defaulted to "All Stop" whenever the drive-control button on the pendent was released. When convinced it was safe to proceed, the user could again depress the button. The emphasis, in other words, is on mission effectiveness versus expediency. It will be interesting to see if this mindset changes over time as the technology matures and users become more confident.

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